Journal of Coastal Research	SI 64	344 - 348	ICS2011 (Proceedings)	Poland	ISSN 0749-0208

Mangrove Forests Submitted to Depositional Processes and Salinity Variation Investigated using satellite images and vegetation structure surveys

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ABSTRACT

Cunha-Lignon, M., Kampel, M., Menghini, R.P., Schaeffer-Novelli, Y., Cintrón, G. and Dahdouh-Guebas, F. 2011. Mangrove Forests Submitted to Depositional Processes and Salinity Variation Investigated using satellite images and vegetation structure surveys. Journal of Coastal Research, SI 64 (Proceedings of the 11th International Coastal Symposium), 344 – 348. Szczecin, Poland, ISSN 0749-0208.

The current paper examines the growth and spatio-temporal variation of mangrove forests in response to depositional processes and different salinity conditions. Data from mangrove vegetation structure collected at permanent plots and satellite images were used. In the northern sector important environmental changes occurred due to an artificial channel producing modifications in salinity. The southern sector is considered the best conserved mangrove area along the coast of São Paulo State, Brazil. Landsat TM5 images from 1997 and 2010 were processed using Geographical Information Systems. Supervised classifications complemented by visual interpretations and ground truth were used to map mangrove areas in both periods. In each permanent plot, all plants were identified and tree diameter, height, and incidence of associated species were recorded. Mean height, basal area dominance, and stem density were also assessed. In the southern sector of the study area, digital image analysis revealed shoreline progradation and mangrove establishment. These sites have demonstrated both vegetation growth and extension. In the northern sector, the satellite image analysis revealed an increase of depositional areas. An important number of associated freshwater plants were observed, inhibiting the establishment of mangrove seedlings or growth of saplings. Despite the high sedimentation rate, which enables mangrove colonization, the low salinity exerts indirect negative influence on mangrove development, considering that it creates good conditions to macrophytes reproduction. Coastal planning requires that the spatial differences be recognized as unique sub-systems due to the hydrodynamic complexity. Both on-the-ground monitoring of the vegetation structure and space-borne remote sensing are important tools to support coastal zone management.

ADDITIONAL INDEX WORDS: *monitoring, remote sensing, permanent plots*

INTRODUCTION

Mangrove forests are among of the most productive and biologically important ecosystems of the world because they provide important and unique ecosystem goods and services to human society and coastal marine systems.

On the other hand, coastal zones around the world are typically populated and pressure for land is often intense. The greatest drivers for mangrove forest loss are direct conversion to aquaculture, agriculture and urban land uses (Duke *et al*., 2007). More recently, sea-level rise could be considered the greatest threat to mangrove (Gilman *et al*., 2008). Despite this, mangroves have a significant role in erosion and accretion along the coastline, trapping sediments (FAO, 2007). Mangrove forests density and intra- and interspecific facilitate the resilience to climate changes (Huxham *et al.,* 2010).

The vegetation structure of mangroves forests are good indicators of sedimentary processes and environmental changes (Cunha-Lignon *et al*., 2009). The effective use of mangroves as indicators depends on a thorough understanding of coastal processes operating in the study area, such as sedimentary dynamics, tides, and currents among others. Mangrove mapping and coastal change detection using remote sensing data to carry out field surveys is a cost-effective way of obtaining results for scientific and management purposes (Souza Filho *et al*., 2006). According to Giri *et al*. (2010), moderate-resolution satellite data such as Landsat contain enough detail to capture mangrove forest distribution and dynamics.

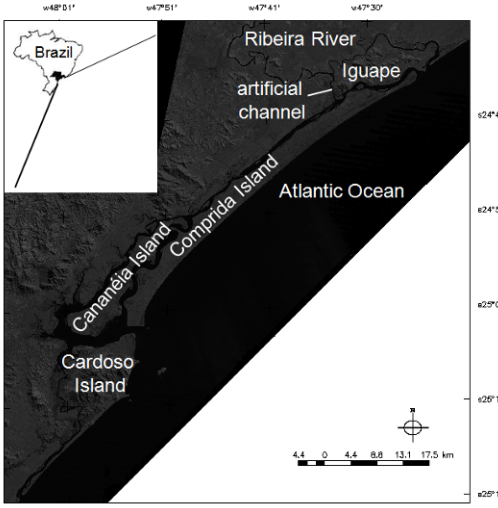

Figure 1. Study area location, the Cananéia-Iguape Coastal System (CICS), on the southern coast of the State of São Paulo, Brazil. Georeferenced Landsat TM5 band 4, from path/rows 219/77 and 220/77, from 17/06/1997 and 24/06/1977, respectively.

The current paper examines the growth and spatio-temporal variation of mangrove forests in response to depositional process and different salinity conditions. Two distinct areas in the Cananéia-Iguape Coastal System, SE Brazil, were assessed using data from time-series satellite Landsat images and monitored vegetation structure in permanent plots.

Study Area

The Cananéia-Iguape Coastal System (CICS), SE Brazil, consists of a complex of lagoon channels (Figure 1), and is part of a World Heritage site by UNESCO, with criteria (vii)(ix)(x), since 1999. The CICS can be divided in two sectors, the northern and the southern, based on geomorphology and environmental conditions.

In the northern sector, important environmental changes occurred over the last 150 years due to the opening of an artificial channel. This artificial channel (Valo Grande), which connects the Ribeira River to the coastal system, produced significant modifications in salinity, depositional patterns and input of heavy metals resulting from lead mining activities into the system, although these ceased in 1995 (Mahiques *et al*., 2009).

The southern sector, which is less influenced by the low salinity of the artificial channel, is considered the best conserved mangrove area along the coast of the State of São Paulo.

METHODS

To provide current mangrove area estimations in the coastal system, polygons were obtained from the Atlas website of SOS Mata Atlântica and INPE (2010). Based on our field expertise in the area since 1999, and QuickBird and IKONOS high-resolution images available in Google Earth, the polygons were modified and new areas were delineated using visual interpretation.

Landsat TM5 images from 1997 and 2010 were processed using SPRING (Câmara *et al*., 1996), version 5.1.6, a Geographic Information Processing System developed and freely distributed by the National Institute for Space Research (INPE - Brazil). Colour compositions 2B3R4G were used in digital processing techniques, including segmentation by region growing, and Battacharya supervised classification complemented by visual interpretation and ground truth to map mangrove areas in both periods and sectors.

The characterisation of structure forest development followed the methodology suggested by Cintrón and Schaeffer-Novelli (1984). Within five transects located along the depositional gradient, 26 permanent plots were established, which varied between $4m^2$ to $150m^2$, according to stem density. New permanent plots were placed when new mangrove stands, with a minimum of 20 individuals, of 1 meter height or more, colonized depositional areas. In each plot, all plants were identified and tree diameter, height, and incidence of associated species were recorded. Mean height, basal area dominance, and stem density were also assessed. In the southern sector, mangrove stands were monitored in January 2001, November 2004, July 2008 and July 2010, whereas in the northern sector, the mangrove forest vegetation structure was described in July 2010. Cluster analysis (UPGMA), using *Statistica* software version 7.0, was applied to the data from January 2001 and July 2010, using parameters for mean height and log-transformed tree density values, originated from permanent plots located in the southern sector.

RESULTS AND DISCUSSION

The area was here estimated as equal to 15,193ha based on the proposed methodology (Figure 2). The map highlighted the southern sector sheltering higher mangrove areas, as result of a larger number of lagoon channels, rivers and creeks. The literature reports smaller areas of mangrove ecosystems, such as 13,751ha from SOS Mata Atlântica and INPE (2010) and 7,200ha from Herz (1991). The main accurate focus on mangrove areas, the knowledge of this coastline, distinct studied periods, or changes in the ecosystem could be the reasons of the disparity between the literature and our results.

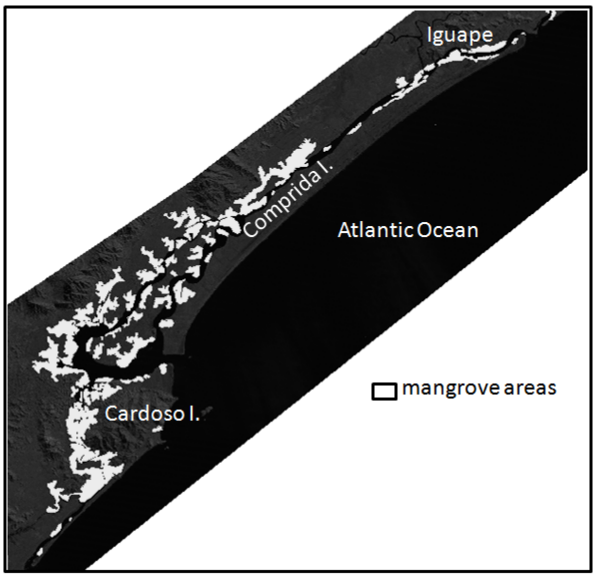

Figure 2. Mosaic of Landsat TM5 image, band 4, from path/rows 219/77 and 220/77, with focus on mangrove areas (white).

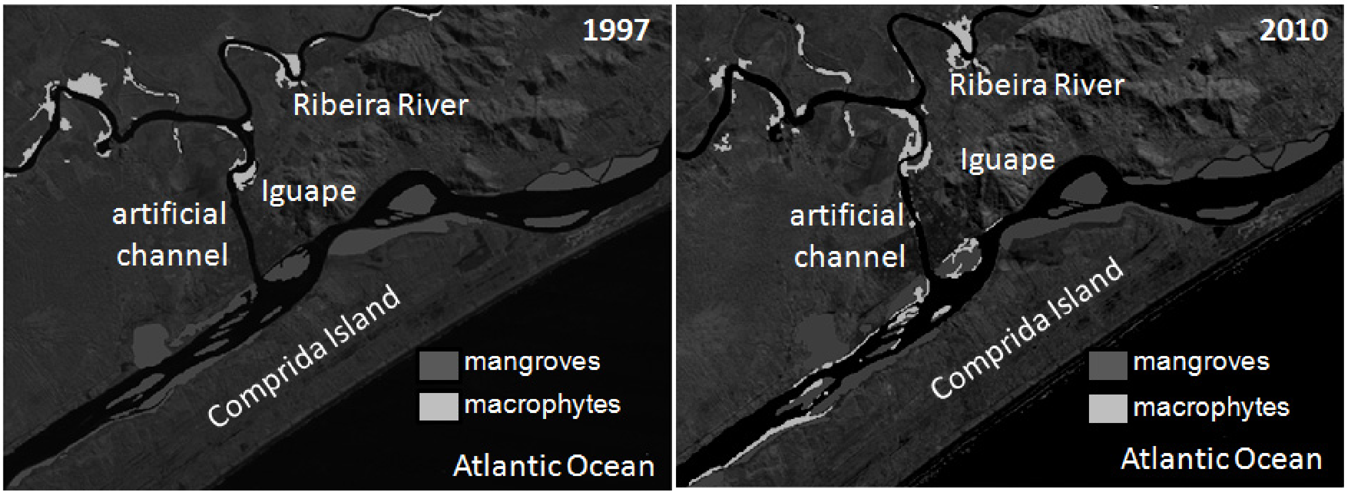

Figure 3. Bhattacharya supervised classification from 1997 and 2010 Landsat images, focus on mangrove and macrophytes areas.

In the northern sector, the supervised digital classification of the 2010 satellite image revealed an important number of associated freshwater species, in the coastal system, close to the artificial channel. On the other hand, in the 1997 image, macrophytes were restricted to the Ribeira River and its meanders (Figure 3). In the southern sector, digital image analysis showed shoreline progradation along the lagoon channels and new areas colonised by mangrove forests. According to Freitas *et al*. (2008), the number of sedimentary islands increased from 58 (in 1938) to 87 (in 2001), the lagoon channel depths decreased and the concentration of clay and silt increased in the coastal system.

In the southern sector, the mangrove forests located in accretion areas were always associated with the smooth cordgrass *Spartina alterniflora* Loiseleur (Poaceae), which helps the fixation and colonization of mangrove seedlings and saplings (Cunha-Lignon *et al*., 2009). In contrast, in the northern sector, *S. alterniflora* was not observed, probably due to the low salinity in this environment (Figure 4). In this northern sector, macrophytes have established (Figure 4), which can inhibit the fixation and establishment of mangroves. This is a case of cryptic ecological degradation, a process whereby typical species are inconspicuously replaced by atypical species without loss of areal extent of the community, but with a probable loss of ecological functionality, as described by Dahdouh-Guebas *et al*. (2005).

Concerning the structural development of mangrove forests, in the southern sector, permanent plots showed an increase of mean tree diameter from January 2001 to July 2010. The establishment of new mangrove zones along the depositional gradient were represented by new plots over the monitored period, such as PA and PB in November 2004 and PC, PD, PE and PF in July 2008 (Figure 5A). The increase of the tree diameters characterises the development from initial to intermediate stages of mangrove forests. The permanent plot 2 represents the mangrove growth, over the monitored period (Figure 5B). Mangrove forests monitored respond to the intense depositional process.

In the southern sector, the monitored period (2001-2010) enabled us to understand local mangrove forest succession. The growth rate is linked to the development stage of each stand. Forests dominated by *Laguncularia racemosa* (L.) Gaertn. F. (Combretaceae) in the initial colonization stage had a growth rate (stem elongation) of about 80cm/year, while forests in the intermediate stage had a rate of about 40cm/year.

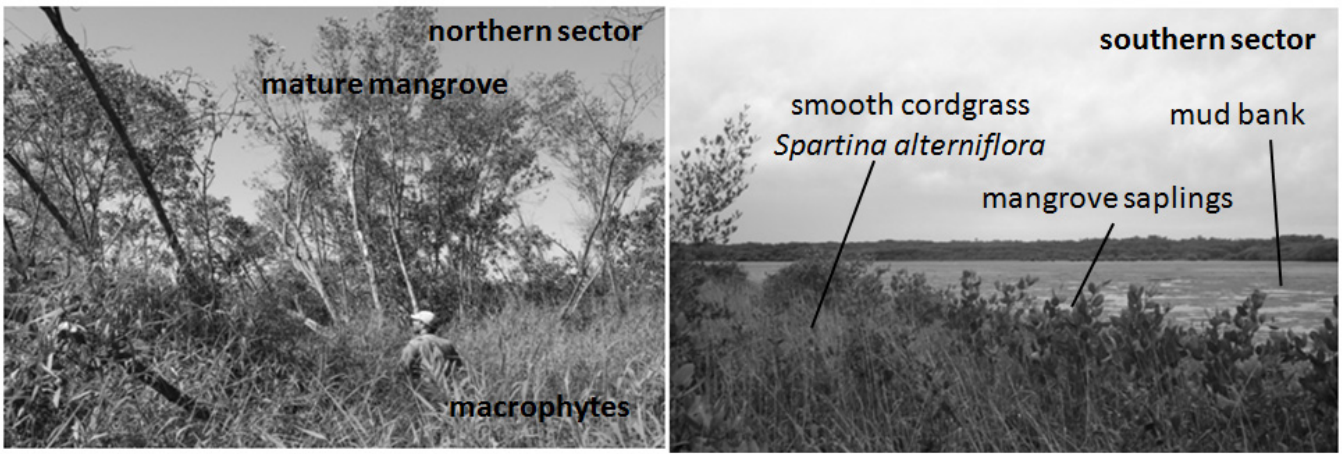

Figure 4. Differences between the northern and southern sectors, with macrophytes dominating mangrove areas in the northern and the *Spartina alterniflora* in the southern sector. Photos taken in July 2010 and July 2008, respectively.

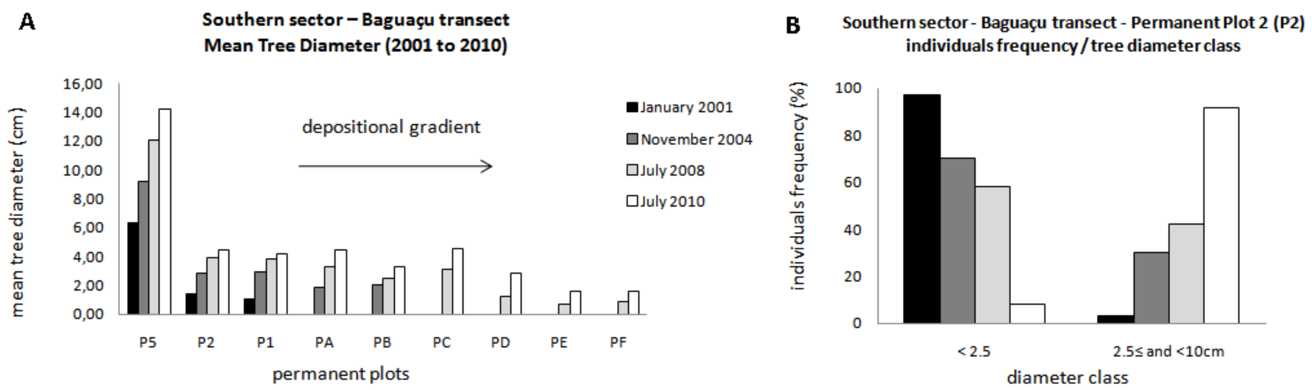

Figure 5. Structural development of mangrove vegetation between January 2001 and July 2010 in permanent plots located along transects in the southern sector. A. Mean tree diameter values, of permanent plots, along the depositional gradient, over the monitored period. B. Individuals frequency of tree diameter classes, from permanent plot 2 (P2), indicating mangrove plant growth, over time.

The UPGMA analysis yielded three groups (A, B and C) indicative of plant development. Group A represented mangrove forests absent in 2001. Group B showed two sub-groups, indicating the initial stage of mangrove forests in 2010 and intermediate stage in 2001 and 2010. Group C designates mangrove forests with high structural development in 2001 and 2010 (Figure 6). The same permanent plot which corresponds to a group in 2001 and to another group in 2010 indicates the mangrove forests development.

The present study demonstrates that mangrove forests are very sensitive to the depositional process and salinity variation along the coastal system and respond to them. In view of climate change and sea-level rise, the importance of mangrove conservation in urban and peri-urban areas to protect coastlines and human local communities must be emphasized.

CONCLUSION

Despite the high depositional rate, that enabled mangroves to colonize new areas, the salinity, which can reach zero, appeared to exert a negative influence on mangrove development.

The salinity reduction caused by the artificial channel has

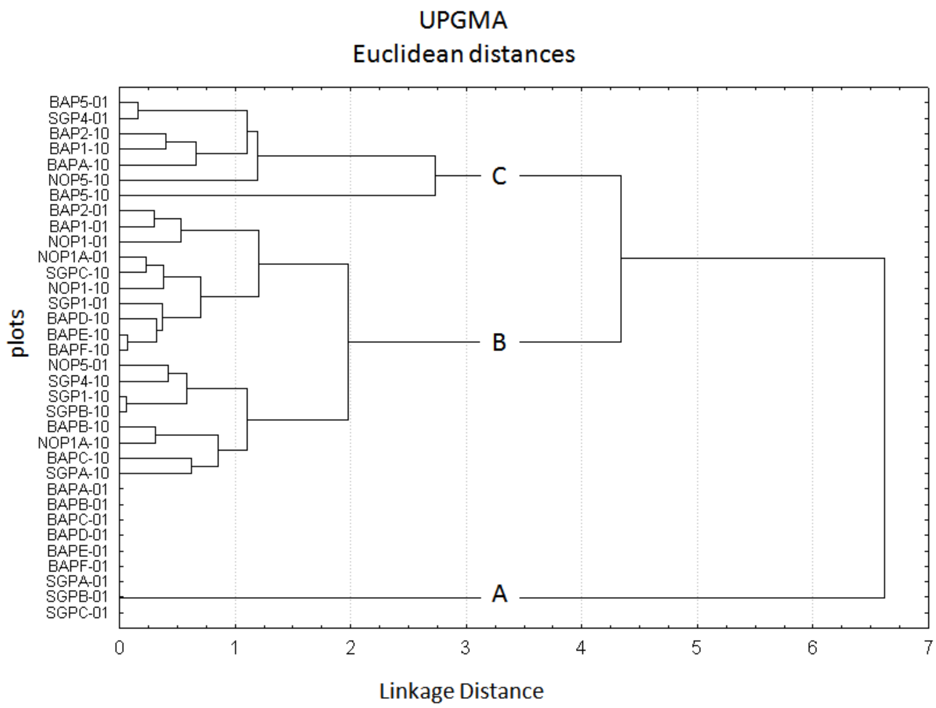

Figure 6. Cluster analysis, considering mean height and log-transformed tree density values, from permanent plots located in the southern sector. Plot code followed by 01 and 10 corresponding to data collection from 2001 and 2010 respectively. Group A indicates plots absent in 2001; Group B indicates mangrove forests with intermediate structural development, and Group C mangrove forests with high structural development.

influenced mangrove forest development in the northern sector, whereas mangrove forests in the southern portion of the study area showed strong positive responses to the active depositional process.

Both on-the-ground monitoring of the vegetation structure of mangrove forests and macrophytes and space-borne remote sensing are important tools to support coastal zone management.

Coastal planning of the Cananéia-Iguape Coastal System requires that spatial differences be recognized as unique sub-systems that exist at the northern and the southern sectors as a result of the hydrodynamic complexity of the system.

As the mangrove vegetation has close linkages with these different hydrodynamic conditions and sedimentary settings, information about mangrove stands in particular sub-settings has to be considered for a complete conservation planning and coastal management.

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ACKNOWLEDGEMENT

This study was undertaken with the financial support of the Fundação de Amparo à Pesquisa do Estado de São Paulo – Brazil (Process 2009/05507-0). We would like to thank the *Instituto Oceanográfico*, from *Universidade de São Paulo* and the Protected Area of Cananéia-Iguape-Peruíbe/ICMBio as well, for permitting the use of the research bases in Cananéia and Iguape, respectively, by the field team. This research has been authorized to develop studies in the Protected Area *Parque Estadual da Ilha do Cardoso*, located in the southern sector of the Coastal System Cananéia-Iguape (Process 260108.003.838/2010). We also thank the National Institute for Space Research - INPE, Brazil for the Landsat images, freely distributed. This study had the precious help of several trainees in the field work, from 2001 to 2010, to whom we would like to show our special gratitude.

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